

Long-duration neutron star X-ray transients in quiescence: the *Chandra* observation of KS 1731–260

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Abstract. I will briefly discuss the implications of the recent quiescent *Chandra* observation of the long-duration neutron star transient KS 1731–260 (Wijnands et al. 2001a) on models for quiescent systems other than the Brown et al. (1998) cooling neutron star model. However, the *Chandra* results are not very constraining; for those models to be consistent with the data, one only has to assume that the system parameters of KS 1731–260 (e.g., the neutron star spin rate and magnetic field properties; orbital parameters) are very similar to those of the other systems. I will also discuss the available quiescent data of other long-duration neutron star transients in the context of the Brown et al. (1998) model.

1. Introduction

X-ray transients spend most of their time in quiescence. The exact emission mechanisms which produce the quiescent X-rays are not yet understood. To explain the neutron star emission, several models have been put forward. So far, the model which assumes that the emission is due to the cooling of the neutron star (e.g., van Paradijs et al. 1987; Verbunt et al. 1994; Brown et al. 1998) has been most successful in reproducing the existing quiescent data and in producing testable predictions. In the most elaborate version of this model, the quiescent luminosity of a particular transient depends on the time averaged accretion rate of this source (Brown et al. 1998). Recently, this model could be tested in a new (although anticipated) way. In early 2001, the neutron star transient KS 1731–260 suddenly became quiescent again, after having actively accreted for more than a decade. A *Chandra* observation was performed on this source only a few months after this transition to test the Brown et al. (1998) model (Wijnands et al. 2001a). If the long duration of the outburst of KS 1731–260 is typical for this source *and* its quiescent time is similar to that of the other neutron star transients (of order years to a few decades), then the system was detected at a luminosity (bolometric luminosity of $\sim 2 \times 10^{33}$ erg s $^{-1}$) and a neutron star temperature ($kT \sim 0.3$ keV) too low compared to what would have been expected. The implications for the Brown et al. (1998) model and its validity for KS 1731–260 are discussed in detail by Wijnands et al. (2001a). If the Brown et al. (1998) model applies to KS 1731–260, its low luminosity might indicate that this system is quiescent for several hundreds of years. This would suggest that several hundreds of such systems might be present in our Galaxy and they might form a new class of X-ray transients (see Wijnands et al. 2001a).

2. Alternative models

The striking similarities between KS 1731–260 and the other systems, combined with the extra assumptions and possible adjustments which have to be made to the Brown et al. (1998) model (Wijnands et al. 2001a), could be used to argue that the cooling neutron star model might not be the correct model to explain the quiescent emission of neutron star transients. Alternative models include residual accretion (see, e.g., Campana et al. 1998; Campana & Stella 2000; Bildsten & Rutledge 2000; Narayan et al. 2001 for discussions) or the models which use a neutron star magnetic field (e.g., Campana et al. 1998; Campana & Stella 2000; Robertson & Leiter 2001¹). In all these models, it is expected that KS 1731–260 should be very similar to the other systems if its system parameters (i.e., the neutron star spin rate and the magnetic field properties; the binary parameters) are very similar to those of the other systems. The fact that the spin rates of KS 1731–260 and Aql X-1 (as inferred from the nearly coherent oscillations observed during type-I X-ray bursts) are very similar (524 Hz versus 549 Hz; Smith et al. 1997; Zhang et al. 1998), indicates that at least the spin rates of those systems are very similar. The orbital parameters of KS 1731–260 are not known, but the recent tentative discovery of the optical counterpart of this system (Wijnands et al. 2001b), might allow a determination of its orbital parameters. Any small differences in the details of the quiescent X-ray properties between the systems (e.g., the exact contribution of the hard power-law tail to the total 0.5–10 keV X-ray luminosity) might simply be due to small differences in the system parameters. However, the arguments why such models have problems explaining the quiescent neutron star emission in general still apply and it remains to be determined which (if any) of the models can produce accurately all of the quiescent properties (e.g., Campana et al. 1998; Bildsten & Rutledge 2000; Menou & McClintock 2001; Narayan et al. 2001).

3. Other quiescent long-duration neutron star transients

Besides KS 1731–260, several more systems can be identified as (possible) long-duration transients. Some of those systems have been observed in quiescence and although their results are not as clean as for KS 1731–260, it is useful to compare them with KS 1731–260 and discuss them in the context of the Brown et al. (1998) model.

3.1. EXO 0748–676

This source was discovered with *EXOSAT* in February 1985 (Parmar et al. 1986) but before that (on 22 May 1980) it was serendipitously observed with *EINSTEIN* with a quiescent luminosity of $\sim 10^{34}$ erg s^{−1} (Parmar et al. 1986; Garcia & Callanan 1999), at least a factor of ten larger than the other systems. Usually, this high quiescent luminosity is explained as due to a relatively high

¹It is interesting to note that Robertson & Leiter (2001) predicted a luminosity of $\sim 10^{33}$ erg s^{−1} for KS 1731–260. Despite this success, their model was proposed to explain the power-law tail in the X-ray spectra of quiescent neutron star systems, which is not the dominate spectral component in KS 1731–260 (Wijnands et al. 2001a).

level of residual accretion during this particular observation (see, e.g., Garcia & Callanan 1999). However, a different explanation can be proposed by comparing this system with KS 1731–260. Since its discovery, EXO 0748–676 has persistently been detected at relatively high luminosities ($> 10^{36}$ erg s $^{-1}$), and, therefore, this source can be regarded as a long-duration transient which has been active now for over 15 years (although it is possible we have witnessed the birth of a new persistent source²). If EXO 0748–676 is typically active *and* quiescent for a few decades, then from the Brown et al. (1998) model, we would expect a luminosity for this system in quiescence of 10^{34-35} erg s $^{-1}$, consistent with what has been observed. So, although KS 1731–260 did not behave as expected (based on the simplest version of the Brown et al. [1998] model), EXO 0748–676 might behave as expected. High sensitivity observations of this latter system are needed when it becomes quiescent again to study its quiescent spectrum. If the luminosity is indeed due to the cooling of the neutron star, then its spectrum should resemble that of the other systems (a black-body-like spectrum), but with a higher neutron star temperature. However, the *EINSTEIN* quiescent data of EXO 0748–676 was fitted using a black-body (although other one-component models fitted equally well) with a kT of ~ 0.2 keV (Garcia & Callahan 1999), which is lower than expected. But, *Chandra* or *XMM-Newton* observations are needed to really constrain its quiescent spectrum.

3.2. MXB 1659–298

MXB 1659–298 was discovered in 1976 (Lewin et al. 1976) and had a clear outburst in 1978 (Lewin et al. 1978). The source was dormant until April 1999 when it was found to be in outburst again (in 't Zand et al. 1999). Since then, the source could be detected with the *RXTE* all sky monitor until the writing of this paper (31 July 2001). Therefore, the source has been active for over two years and might also be considered a long-duration transient (see also Wijnands et al. 2001a), although two years is relatively short compared to the 11.5 years of KS 1731–260 and the more than 15 years of EXO 0748–676. Verbunt (2001) reported that during a 1991 *ROSAT*/PSPC observation, the source was not detected with an upper limit on the unabsorbed flux of $1 - 2 \times 10^{-14}$ erg s $^{-1}$ cm $^{-2}$ (0.5–10 keV; estimated with W3PIMMS³ assuming a black-body spectrum with $kT \sim 0.3$ keV and using the count rate values provided by Verbunt [2001] but with the updated column density provided by Oosterbroek et al. [2001]; see also the latter paper for a similar estimate but for 0.2–2.4 keV). The distance estimates to this source (as obtained from radius expansion bursts) range from 10 kpc (Muno et al. 2001) to 13 kpc (Oosterbroek et al. 2001), resulting in a 0.5–10 keV luminosity upper limit of $1-4 \times 10^{32}$ erg s $^{-1}$. Assuming that the upper limit on the bolometric luminosity is only a factor of a few higher (e.g., Rutledge et al. 2000), then this source had an even lower quiescent luminosity than KS 1731–260. If the time averaged mass accretion rate of the past 25 years in MXB 1659–298 is a good indication of its time averaged mass accretion

²The difference between a persistent source and a long-duration transient is somewhat arbitrary because in principle every persistent source turned on in the past and will turn off in the future.

³W3PIMMS can be found at <http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html>

rate of the past several thousands of years, then also this system is too dim in quiescence. It is also possible that the first two short outbursts are more typical for this source and the long outburst is a rare phenomenon (note that this is also possible for the other long-duration transients discussed here, including KS 1731–260). Regardless of the true averaged outburst duration of this source, high sensitivity observations are needed when it becomes dormant again to test the effect of the long period of accretion on the neutron star crust and interior.

3.3. 4U 2129+47

4U 2129+47 was considered to be a persistent source until in 1983 the source was not detected with *EXOSAT* (Pietsch et al. 1983, 1986). Although the exact beginning of its long active episode is unknown (so the duration of its active state is unclear), it is possible that 4U 2129+47 is also a long-duration X-ray transient (although it is possible that we have witnessed the turn off of a persistent source). The source was detected in quiescence with the *ROSAT*/HRI at $3 \times 10^{33} \text{ erg s}^{-1}$ (0.3–2.4 keV; Garcia 1994) and the *ROSAT*/PSPC at $6 \times 10^{32} \text{ erg s}^{-1}$ (0.5–10 keV; Garcia & Callanan 1998; the bolometric luminosity would be about a factor 2 higher; Rutledge et al. 2000). The X-ray spectrum of the source in the latter data set was consistent with a black-body with a kT of approximately 0.2 keV. If the outburst and quiescent duration so far observed for 4U 2129+47 are typical for this source, then these luminosity and black-body temperature are lower than expected from the Brown et al. (1998) model. However, during the long episode during which the source could not be detected at high levels (since September 1983; Pietsch et al. 1983) and the first detection of the source in quiescence (December 1991; Garcia 1994), the source could have cooled down. However, the exact cooling time of neutron stars is unknown and is model dependent.

3.4. Globular cluster source X 1732–304 (Terzan 1)

In the early eighties, *Hakucho* detected a bursting X-ray source in the globular cluster Terzan 1 (Makishima et al. 1981; Inoue et al. 1981). In 1985, a steady X-ray source was detected (X 1732–304) consistent with this globular cluster and it is most likely the same source as the bursting source (Skinner et al. 1987). Since then, it has persistently been detected at luminosities between a few times $10^{35} \text{ erg s}^{-1}$ and $\sim 10^{37} \text{ erg s}^{-1}$ (see Figure 3 of Guainazzi et al. 1999). Recently, Guainazzi et al. (1999) reported that during a *BeppoSAX* observation this source could only be detected at a 2–10 keV luminosity of $1.4 \sim 10^{33} \text{ erg s}^{-1}$ (for a distance of 4.5 kpc), with a spectrum consistent with a black-body spectrum ($kT \sim 0.34 \text{ keV}$) plus a power law (with photon index of ~ 1). These spectral parameters are very similar to those of the neutron star X-ray transients in quiescence and it is likely that X 1732–304 became suddenly quiescent after having actively accreted for over 15 years (see Guainazzi et al. 1998). Thus this source is a clear example of a long-duration transient, similar to KS 1731–260.

Using the spectral parameters given by Guainazzi et al. (1998), the quiescent luminosity of X 1732–304 can be converted into a 0.5–10 keV luminosity of $\sim 5 \times 10^{33} \text{ erg s}^{-1}$. The bolometric luminosity will be most likely about a factor of two higher ($\sim 10^{34} \text{ erg s}^{-1}$; see, e.g., Rutledge et al. 2000). This is considerably higher than the bolometric luminosity of KS 1731–260 in quiescence and might indicate that X 1732–304 behaved more as expected in quiescence due to

its prolonged period of high accretion (based on the Brown et al. [1998] model). The fact that the *BeppoSAX* quiescent observation of this source was taken at approximately two years after the last detection of the source above $\sim 10^{35}$ erg s $^{-1}$ (Molkov et al. 2001), demonstrates that the exact moment when the source became dormant is unknown. The source could have been in quiescence for about two years before the *BeppoSAX* observation and it could be initially even more luminous and could have cooled down considerably (this depends on the exact cooling time of the neutron star crust and interior). However, due to the low angular resolution of *BeppoSAX*, it can also not be excluded that the detected source might not be X 1732–304 but another low-luminosity globular cluster source (see also Guainazzi et al. 1998). In that case, X 1732–304 might be less luminous than assumed in the above discussion and might be more similar to KS 1731–260. A *Chandra* image of Terzan 1 will reveal whether or not the *BeppoSAX* source is indeed X 1732–304 (its position from a *ROSAT*/HRI observation is known to $\sim 5''$; Johnston et al. 1994) and whether the luminosity is contaminated by other nearby sources. X 1732–304 might be an excellent candidate to test the cooling neutron star model proposed by Brown et al. (1998).

4. Conclusions

The quiescent *Chandra* observation of KS 1731–260 can constrain the cooling neutron star models proposed for the quiescent emission of neutron star transients. However, it is less constraining for other types of models. In those models, KS 1731–260 is expected to be very similar to the other quiescent systems if its orbital parameters and/or its neutron star parameters (i.e., magnetic field parameters, spin rate) are very similar to those of the other systems.

It is clear that KS 1731–260 is part of a group of transients which do not disappear after a few weeks to months but are active for years to decades. Several such sources can be identified for which observations were also performed in quiescence. Two of those systems, EXO 0748–676 and X 1732–304 might indeed be brighter in quiescence than the other systems, possible due to the heating of the neutron stars during the long periods of accretion. Three other systems (4U 2129+47, MXB 1659–298, and KS 1731–260) seem to have anomalously low luminosities in quiescence and might prove to be very constraining for the models dealing with the heating of the crust and the core of neutron stars in X-ray binaries. However, only for KS 1731–260 is a clear picture available about its outburst behavior (i.e., the exact mass accretion rate during outburst; the outburst duration) *and* was the quiescent observation performed within a few months after the source became quiescent again. For the other sources, the outburst behavior is not well known (i.e., its duration; e.g., EXO 0748–676, MXB 1659–298, 4U 2129+47), the quiescent observation were performed years after (4U 2129+47, X 1732–304) or before (MXB 1659–298, EXO 0748–676) a long-duration outburst, and source confusion might play a role (X 1732–304).

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